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Model of the Correlation between Lidar Systems and Wind Turbines for Lidar Assisted Control

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ABSTRACT

Investigations for lidar assisted control to optimize the energy yield and to reduce loads of wind turbines increased significantly in recent years. For this kind of control it is crucial to know the correlation between the rotor effective wind speed and the wind preview provided by a nacelle or spinner based lidar system. If on the one side the assumed correlation is overestimated, the uncorrelated frequencies of the preview will cause unnecessary control action, inducing undesired loads. On the other side the benefits of the lidar assisted controller will not be fully exhausted, if correlated frequencies are filtered out.

To avoid these uncertainties, this work presents a method to model the correlation between lidar systems and wind turbines using Kaimal wind spectra. The derived model accounts for different measurement configurations and for different turbine sizes. The method is evaluated in two steps: At first the model is compared to the results from a lidar simulator to prove that the model is able to reproduce the effect of volume measurement, limited measurement points and scanning time. In a second step the model is augmented by a model for the decay due to wind evolution and compared to real measurement data with promising results. In addition an example is given, how this model can be used to design an optimal controller for a lidar system with fixed parameters and a given turbine and how the pattern of a scanning lidar system is optimized for a given turbine to improve the correlation.

1 REQUIREMENTS FOR LIDAR ASSISTED CONTROL

Reducing fatigue and extreme loads of the structure is an important design goal for large wind turbines control. Transient events such as gusts represent an unknown disturbance to the control system. Conventional feedback controllers can

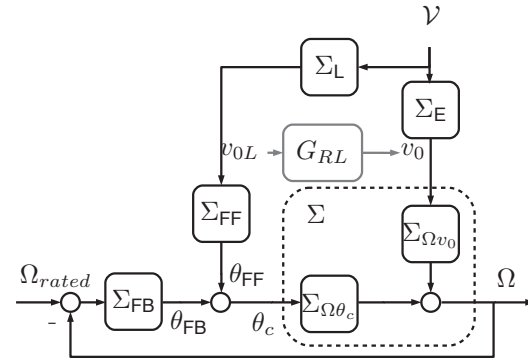


Figure 1: Feedforward control: The feedforward controller Σ_{FF} tries to compensate the effects of the wind field \mathcal{V} to the rotor speed Ω .

only provide delayed compensation for such excitations, since the disturbance effects must propagate through the entire wind turbine before showing its effects in the measured outputs. This usually results in additional loads for the wind turbine and requires high actuator rates for the disturbance compensation. Those effects can be avoided, if the wind ahead of the wind turbine is measured by remote sensing techniques such as lidar and the information is fed to the turbine controller.

The magnitude of load reduction depends on the quality of the wind preview expressed by the correlation of the Lidar measurements and the turbine reaction. In this section the requirements of the correlation for lidar assisted control are derived by a description of a feedforward collective pitch controller.

The feedforward controller (see Figure 1) is based on the work in [1] and combines the baseline feedback controller with a feedforward update. The main control goal of the collective pitch feedback controller Σ_{FB} is to maintain the rated rotor speed Ω_{rated} . The system Σ is disturbed by a wind field \mathcal{V} , which can be measured by a lidar system Σ_L in front of the turbine before reaching the rotor. If the wind would not change on its way ($\Sigma_E = 1$)

and in the case of perfect measurement the measured wind speed v_{0L} and the rotor effective wind speed v_0 are equal. The disturbance could be perfectly compensated by a feedforward controller $\Sigma_{FF} = -\Sigma_{\Omega\theta_c}^{-1} \Sigma_{\Omega v_0}$, if the influence on the generator speed of the wind $\Sigma_{\Omega v_0}$ and the pitch angle $\Sigma_{\Omega\theta_c}$ is known and $\Sigma_{\Omega\theta_c}$ is invertible.

In reality v_0 cannot be measured perfectly due to the limitation of the lidar system Σ_L and the wind evolution Σ_E . Therefore the needed feedforward controller is:

$$\Sigma_{FF} = -\Sigma_{\Omega\theta_c}^{-1} \Sigma_{\Omega v_0} \Sigma_L^{-1} \Sigma_E. \quad (1)$$

Due to the interaction with the turbine and missing technology, modeling and verifying the wind evolution Σ_E is very complicated. Also not all information of the wind field \mathcal{V} can be reconstructed by the inverse of a real limited lidar system Σ_L . However, if the transfer function G_{RL} from the measured wind speed to the rotor effective wind speed can be used to exploit all information captured by the lidar system:

$$\Sigma_{FF} = -\Sigma_{\Omega\theta_c}^{-1} \Sigma_{\Omega v_0} G_{RL}. \quad (2)$$

For real time applications the transfer function G_{RL} can be obtained from measurements and approximated by a standard low pass filter. Therefore the cut-off frequency ($-3dB$) of the corresponding filter can be considered as a quality criterion for the correlation. In the following sections a analytic way is presented to estimate the both the transfer function G_{RL}

$$G_{RL} = \frac{S_{RL}}{S_{LL}}, \quad (3)$$

and the coherence γ_{RL}

$$\gamma_{RL} = \frac{|S_{RL}|^2}{S_{RR}S_{LL}}. \quad (4)$$

2 ROTOR AVERAGED SPECTRUM

The model of the rotor averaged spectrum $S_{v_0 v_0}$ is derived from Kaimal wind spectra. The hub height power spectral density of the longitudinal velocity component is given in [2] by the equation:

$$\frac{f S_{HH,1}(f)}{\sigma_{HH,1}^2} = \frac{4f L_1 / v_{HH}}{(1 + 6f L_1 / v_{HH})^{(5/3)}}, \quad (5)$$

where v_{HH} and σ_{HH} are the mean and standard deviation of the longitudinal velocity component on hub height. The spatial correlation of a longitudinal velocity component with distance r_{ij} of two points with coordinates (y_i, z_i) and (y_j, z_j) is defined as

$$\gamma_{ij}(f) = \exp\left(-\underbrace{12\sqrt{(f/v_{HH})^2 + (0.12/L_1)^2}}_{\kappa} r_{ij}\right) \quad (6)$$

The rotor averaged spectrum can be derived by an average of the cross and auto spectrum densities of all points and combinations in the rotor plane D with rotor radius R :

$$S_{RR}(f) = \frac{1}{(\pi R^2)^2} \int_{D_j} \int_{D_i} S_{ij}(r_{ij}, f) dy_i dz_i dy_j dz_j \quad (7)$$

An explicit solution of (7) can be found showing the complexity by

$$S_{RR}(f) = 2(R\kappa(-9\pi {}_0\tilde{F}_1(; 2; (R\kappa)^2) - 6\pi L_2(2R\kappa) - 8R\kappa + 6\pi I_0(2R\kappa) + 3\pi) + 3\pi L_1(2R\kappa)) / (3\pi(R\kappa)^3) S_{HH,1}(f) \quad (8)$$

where ${}_0\tilde{F}_1$ is the regularized confluent hypergeometric function, L_n is the modified Struve function, and I_0 is the modified Bessel function of the first kind.

The discrete form of the averaged rotor spectrum can be calculated by with n points inside the rotor area

$$S_{RR}(f) = \frac{S_{HH,1}(f)}{n^2} \sum_{i=1}^n \sum_{j=1}^n \gamma_{ij}(f). \quad (9)$$

3 CORRELATION OF A PERFECT STARRING LIDAR

Ignoring the filtering effect of a lidar, assuming Taylor's Hypothesis to be fully valid (no wind evolution), the spectrum of a starring lidar can be modeled by

$$S_{LL}(f) = S_{HH,1}(f). \quad (10)$$

Then the cross spectrum between the starring lidar and the rotor is

$$S_{RL}(f) = \frac{1}{\pi R^2} \int_D S_{Hj}(r_{Hj}, f) dy_j dz_j, \quad (11)$$

where S_{Hj} means the cross spectrum of the hub and the point j with distance r_{Hj} .

This can be solved with

$$\begin{aligned} S_{RL}(f) &= \frac{S_{HH,1}(f)}{\pi R^2} \int_0^{2\pi} \int_0^R r \gamma_{Hj}(f) dr d\phi \\ &= \frac{2S_{HH,1}(f)}{R^2 \kappa^2} \left(1 - \frac{R\kappa + 1}{\exp(R\kappa)}\right). \end{aligned} \quad (12)$$

With (3), (4) and

$$k = \frac{2\pi f}{\bar{u}} \quad (13)$$

the transfer function G_{RL} and the coherence γ_{RL} can be calculated over the wavenumber k , independent of the mean wind speed \bar{u} .

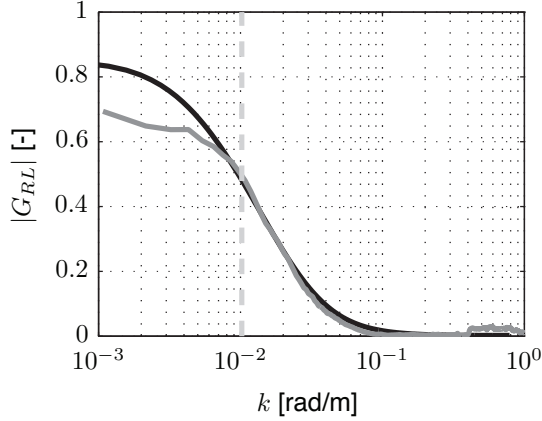


Figure 2: Transfer function for a nacelle anemometer and a turbine with $D = 116m$: analytic (black) and measured (gray). Maximum wavenumber $\hat{k} = 0.01 \text{ rad/m}$ (dashed).

This model cannot be evaluated with a real lidar system, because wind evolution and volume measurement cannot be neglected. Therefore an anemometer on a 5 MW turbine is compared to a nacelle anemometer. Figure 2 shows that the modeled transfer function fits to the data.

4 CORRELATION OF A REAL SCANNING LIDAR

For real scanning lidar system the model has to be extended by a model for the volume measurement and wind evolution. Here the model [3] is used. To model the volume measurement, a Gaussian shape weighting function $f_L(a)$ depending on the distance a to the focus point with full width at half maximum (FWHM) of $W = 30m$ is used, following the considerations of [4], [5] and [6]:

$$f_L(a) = \frac{e^{-4 \ln 2 (a/W)^2}}{\int_{-\infty}^{\infty} e^{-4 \ln 2 (a/W)^2} da} = \frac{2 \ln 2 e^{-4 \ln 2 (a/W)^2}}{W \sqrt{\ln 2 \pi}}. \quad (14)$$

With the weighting function it is possible to calculate the line-of-sight wind speed of each focus point with $f_L(a)$ by

$$v_{los} = \int_{-\infty}^{\infty} (l_x u(a) + l_y v(a) + l_z w(a)) f_L(a) da, \quad (15)$$

where $[l_x \ l_y \ l_z]^T$ is the normalized laser beam vector and $[u(a) \ v(a) \ w(a)]^T$ the wind vector at the distance a to the focus point.

As LIDAR systems measure only the wind speed in line-of-sight direction, the three dimensional wind vector is reconstructed using the assumption

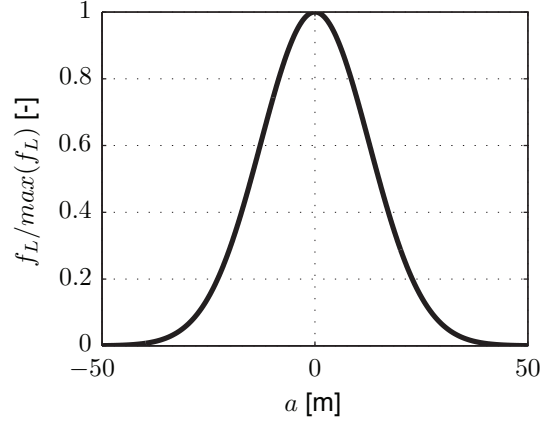


Figure 3: Normalized range weighing function $f_L(a)$ for the considered LIDAR system.

of perfect yaw alignment with the wind direction. If the turbine is perfectly aligned with the wind, the estimated lateral and vertical wind components are assumed to be zero and the longitudinal component $\hat{u}_{i_{fp}}$ for each focus point can be calculated as

$$\hat{u}_{i_{fp}} = v_{los}/l_x. \quad (16)$$

For each distance i_{fd} the longitudinal wind component $\hat{u}_{i_{fp}}$ is then averaged over the n_{fp} focus points of the last trajectory by

$$v_{i_{fd}} = \sum_{i_{fp}}^{n_{fp}} \hat{u}_{i_{fp}} / n_{fp} \quad (17)$$

for a rotor effective value and the obtained time series of the measurements $v_{i_{fd}}$ is time-shifted according to Taylor's frozen turbulence hypothesis and combined to the rotor effective wind speed:

$$v_{0L} = \sum_{i_{fd}}^{n_{fd}} v_{i_{fd}} / n_{fd} \quad (18)$$

The spectrum of a scanning lidar can then be found by a Fourier transform of (18), including (17), (16) and (15) using a weighting function such as (14) and a wind evolution model such as [3].

5 LIDAR SYSTEM OPTIMIZATION

The proposed model can be used to optimize a lidar system. To determine the optimum correlation of a lidar system with three independent beams on a turbine with $D = 40m$, the measurement distance x and the scan radius r is varied, see Figure 5. The value of maximum wavenumber \hat{k} at $-3dB$ below the steady value of the transfer

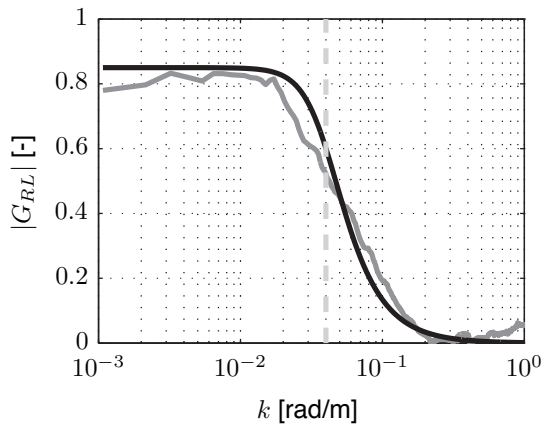


Figure 4: Transfer function for a scanning lidar and a turbine with $D = 116m$: analytic (black) and measured (gray). Maximum wavenumber $\hat{k} = 0.04 \text{ rad/m}$ (dashed).

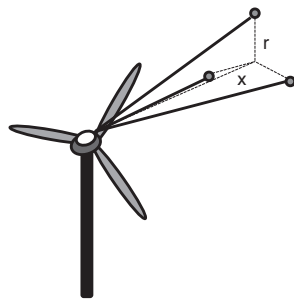


Figure 5: Scope of lidar with three beams.

function is shown in Figure 6. A optimum value ($\hat{k} = 0.03 \text{ rad/m}$) can be found at $x = 40m$ and $r = 12m$.

6 CONCLUSION AND OUTLOOK

This work presents a model to estimate the correlation between a lidar and a turbine, considering volume measurements, different scanning patterns and wind evolution. A criterion for lidar assisted control is derived: for a collective pitch feedforward controller the transfer function from the measured wind speed to the rotor effective wind speed obtained from turbine data has to be used to filter the data. For real application this transfer function has to be fitted to a standard filter and therefore the $-3dB$ of considered as a useful criterion for the the correlation between a lidar and a turbine.

The model can be used to optimize the configuration of a lidar system such as probe volume and scan pattern.

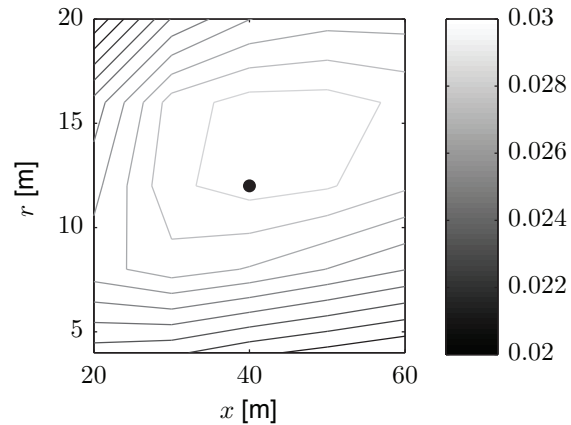


Figure 6: Maximum wavenumber of lidar with three beams on a turbine with $D = 40m$ (dashed) and different distances and radii.

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